AD-A284 452

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

(1)

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	14 Mar 93	Final - 1 Jul 92 - 14 Jan 93

4. TITLE AND SUBTITLE
A Center of Excellence in Rotary Wing Aircraft Technology, Final Report - Phase II - Program Maturation Phase, 15 January 1988 - 14 January 1993

5. FUNDING NUMBERS
DAAL03-88-C-0003

6. AUTHOR(S)
D.P. Schrage, R.B. Gray, E.A. Armanios, A.J. Calise, J.I. Craig, S.V. Hanagud, D.H. Hodges, N.M. Komerath, D.A. Peters, G.A. Pierce, J.V.R. Prasad, L.N. Sankar

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Center of Excellence in Rotary Wing Aircraft Technology (CERWAT), School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 25461.77-~~EG~~-RW

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
This report summarizes the research performed by CERWAT faculty in the following fields critical to the development of rotary wing aircraft: aerodynamics, aeroelasticity, structures and materials, and flight mechanics and controls. It covers activity during the program maturation phase of the Army's centers of excellence program for rotorcraft technology.

14. SUBJECT TERMS
aerodynamics, aeroelasticity, structures, materials, flight mechanics, controls, computational fluid dynamics, flow visualization

15. NUMBER OF PAGES
37

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

A CENTER OF EXCELLENCE

IN

ROTARY WING AIRCRAFT TECHNOLOGY

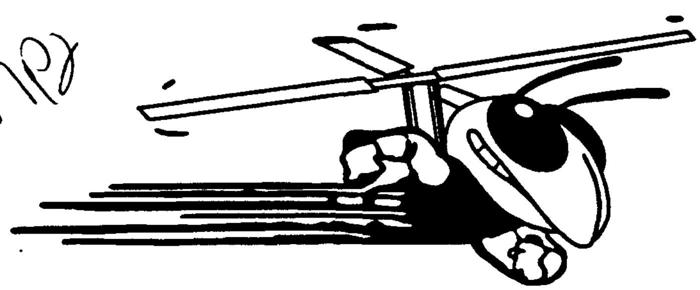
FINAL REPORT

PHASE II - PROGRAM MATURATION PHASE
15 January 1988 - 14 January 1993

AUTHORS:
R.B. Gray
DP. Schrage,
E.A. Armanios,
A.J. Calise
J. I. Craig
S.V. Hanagud
D.H. Hodges,
N.M. Komerath
C.M. McKeithan
D.A. Peters
G.A. Pierce
J.V.R. Prasad
L.N. Sankar
C. Wang
J.C. Wu

U.S. ARMY RESEARCH OFFICE

CONTRACT DAAL3-88-C-0003



GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF AEROSPACE ENGINEERING

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FOREWORD

This report summarizes the research conducted by the Georgia Institute of Technology (GIT) Center of Excellence in Rotary Wing Technology (CERWAT) during the second phase of the Army's rotorcraft Centers of Excellence (COE's) program. The major accomplishments achieved during the first two phases of CERWAT are illustrated in Figure 1 along with some items addressing the scope of Phase III, the Program Sustainment Phase, which began on 1 November 1992 and runs for three years. You will note that for this third phase, the name CERWAT has been changed to CERT, Center of Excellence in Rotorcraft Technology, to reflect the Army's name for Phase III of the rotorcraft COE program.

As can be seen in Figure 1, there were five key objectives identified for Phase II - the Program Maturation Phase. The first objective was to add the flight mechanics and controls discipline to the research program. This addition provided the missing critical discipline for advancing rotorcraft technology and served as a catalyst for integrating controls technology with the other rotorcraft disciplines - aerodynamics, aeroelasticity, and structures and materials. The second objective was to emphasize interdisciplinary research among the four critical rotorcraft disciplines. This has been accomplished to a large extent as discussed in the write-ups on the individual research tasks. The third objective was to stress rotorcraft related research development. The negotiated funding profile for CERWAT is illustrated in Figure 2. As can be seen, the funding was greatly reduced in FY92 and there was no assurance of a Phase III program. As a result of active research program development by all of the CERWAT researchers, rotorcraft related research has grown substantially during the Phase II program as illustrated by Figure III, although that growth has leveled off and rotorcraft related research is expected to diminish in FY93 due to Department of Defense funding cuts. It would be difficult to sustain the GIT rotorcraft COE without an Army Phase III Program. The fourth objective for Phase II was to emphasize Army officer graduate student recruitment. During CERWAT Phase II, 14 Army officers received M.S. or Ph.D. degrees. This was accomplished through talks given at the Army Aviation Officers Advanced Course at Fort Rucker, AL, and mostly through word of mouth from Army officers who graduated and knew the quality of the CERWAT program. The final objective of CERWAT Phase II was to emphasize technology transfer to industry and government the research results that were ready for application in the next phase of the research and development cycle. The Georgia Tech

CERWAT has been very active in this area and specific discipline results are addressed in the task write-ups. Some overall examples are provided in Figure 4.

In summary, it can be seen that the Georgia Tech CERWAT accomplished the objectives it set for itself during the Phase II program. We feel that we have a mature program and look forward to executing the Phase III - Program Sustainment Phase. Objectives we have established for Phase II are as follows:

- Work with industry and government in identifying needs and areas where CERT can contribute
- Build on individual disciplinary, multi-disciplinary, and interdisciplinary successes
- Explore opportunities available as a result of new rotorcraft and related initiatives
- Play more of a leadership role in advancing rotorcraft technology.

GEORGIA TECH — CERWAT

CERWAT PROGRAM PHASES

PHASE I - PROGRAM INITIATION AND DEVELOPMENT (1982-1987) CERWAT

- CURRICULUM DEVELOPMENT (3 COURSES →16 COURSES)
- FACILITY UPGRADE AND DEVELOPMENT (2 FACILITIES UPGRADED, 3 NEW FACILITIES DEVELOPED)
- FACULTY RECRUITMENT (8 FACULTY →14 FACULTY)
- CERWAT FELLOWSHIP PROGRAM DEVELOPMENT (16 FELLOWS)
- RESEARCH PROGRAM DEVELOPMENT (3 DISCIPLINES: AERODYNAMICS, AEROELASTICITY, AND STRUCTURES & MATERIALS)

PHASE II - PROGRAM MATURATION (1988 - 1993) CERWAT

- FLIGHT MECHANICS & CONTROLS DISCIPLINE ADDED
- INTERDISCIPLINARY RESEARCH EMPHASIZED
- ROTORCRAFT RELATED RESEARCH DEVELOPMENT
- ARMY OFFICER GRADUATE STUDENT RECRUITMENT
- TECHNOLOGY TRANSFER EMPHASIZED

PHASE III - PROGRAM SUSTAINMENT (1993-1996) CERT

- ARMY FUNDING CUT IN HALF
- INDUSTRY COST SHARING REQUIRED AND UNIVERSITY COST SHARING INCREASED
- A FLIGHT SIMULATION TASK ADDED

Figure 1.

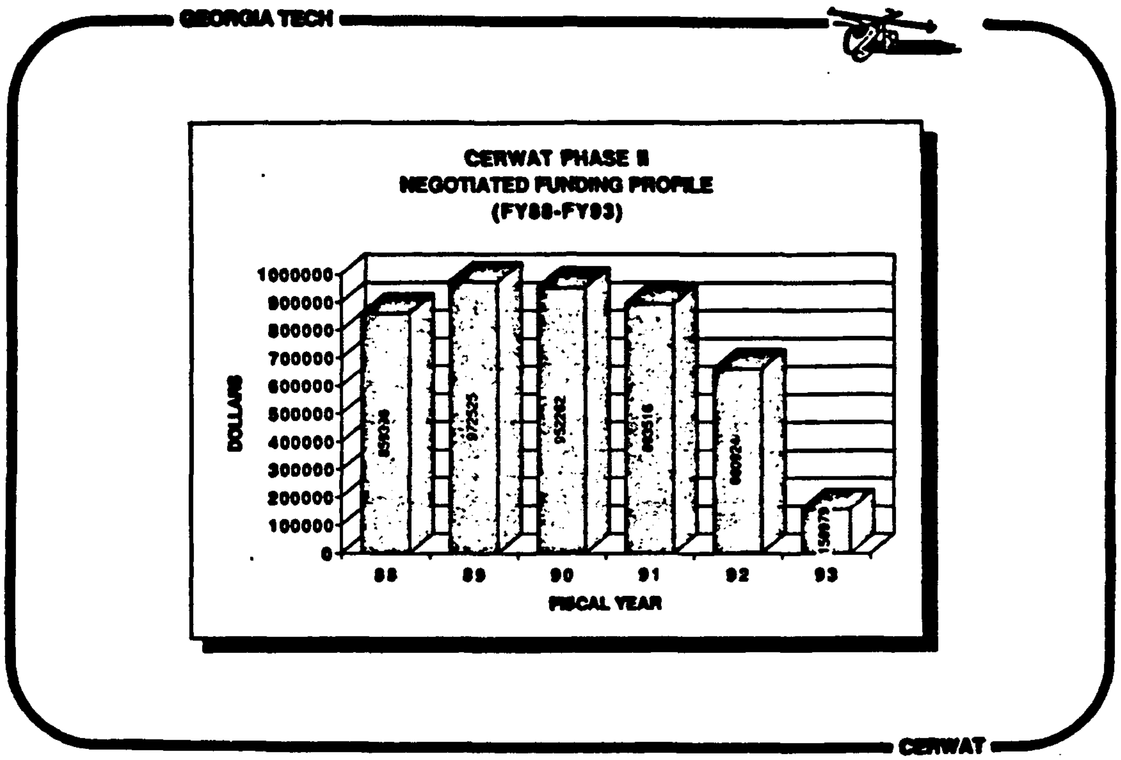

Figure 2.

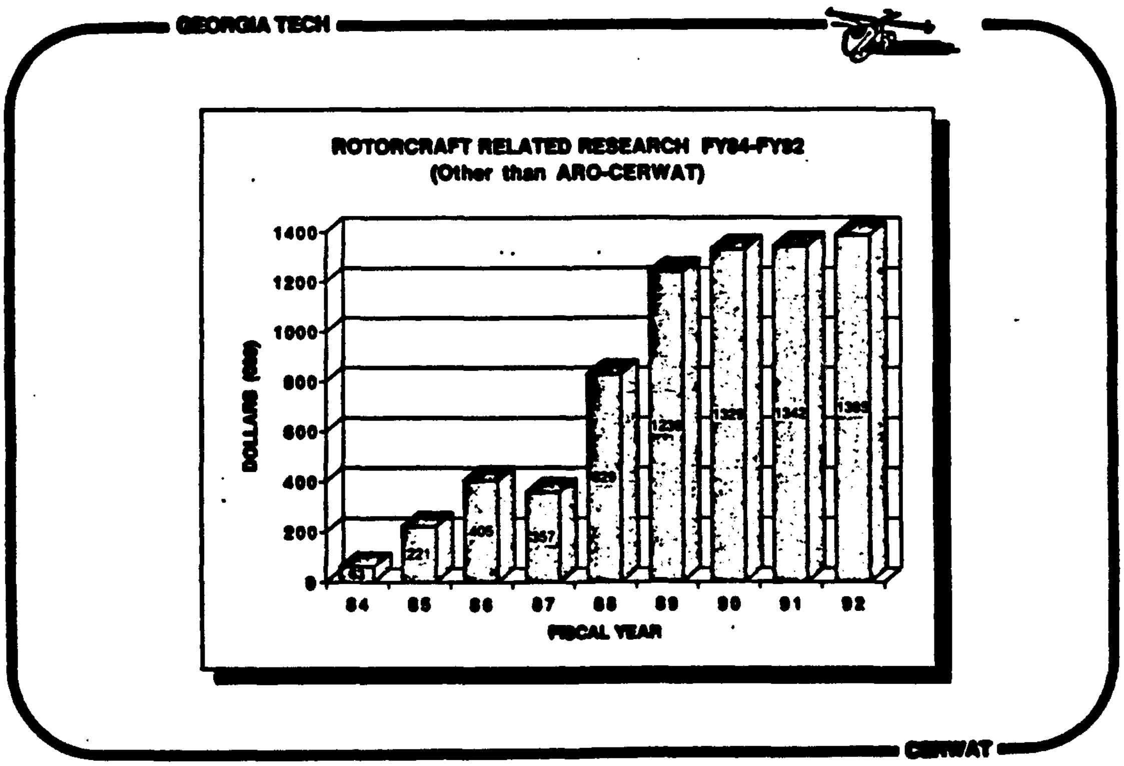

Figure 3.

GEORGIA TECH

CERWAT INITIATIVES TO EXPAND ROTORCRAFT RESEARCH ACTIVITIES FOR ADVANCING ROTARY WING TECHNOLOGY

- **Simulation and Modeling**
  - **Flight Simulation (FLIGHT SIM) Laboratory**
  - **2GCHAS Enhancement Program**
  - **PM-TRADE/DARPA ADST Program**
- **Artificial Intelligence and Robotics**
  - **RPA Mission Effectiveness**
  - **Aerial Robotics Competition**
- **Low Observables**
  - **CFD Modeling**
- **Safety Enhancements**
  - **USAF PAVE LOW/PAVE HAWK Structural Integrity Program (SIP)**
  - **Tri-Service Flight Data Recorder Program**
- **Diversification**
  - **Tiltrotor and HSRC**
  - **FAA and Commercial Programs.**

Figure 4.

TABLE OF CONTENTS

FINAL REPORT

1. ARO PROPOSAL NUMBER: P-25461-EG-RW
2. PERIOD COVERED BY REPORT: 1 July 1992 - 14 January 1993
3. TITLE OF PROPOSAL: Continuation of Rotorcraft Centers Program
4. CONTRACT OR GRANT NUMBER: DAAL3-88-C-0003
5. NAME OF INSTITUTION: GEORGIA INSTITUTE OF TECHNOLOGY SCHOOL OF AEROSPACE ENGINEERING
6. AUTHOR(S) OF REPORT: R.B. Gray, DP. Schrage, E.A. Armanios, A.J. Calise, J I. Craig, S.V. Hanagud, D.H. Hodges, N.M. Komerath, C.M. McKeithan, D.A. Peters, G.A. Pierce, J.V.R. Prasad, L.N. Sankar, J.C. Wu

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Funk, R., Fawcett, P.A., and Komerath, N.M., "Instantaneous Velocity Fields in a Rotor Wake By Spatial Correlation Velocimetry". Accepted by the AIAA 24th Fluid Dynamics Conference, Orlando, Fl.

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Kim, J-M., Komerath, N.M., and Liou, S-G., "Vorticity Concentration at the Edge of the Inboard Vortex Sheet". Accepted for presentation at the 49th AHS Forum, St. Louis, MO, May 1993.

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8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Co-Principal Investigators: R. B. Gray and D. P. Schrage

Faculty: R.B. Gray, D.P. Schrage, E.A. Armanios, A.J. Calise, J.I. Craig, S.V. Hanagud, D.H. Hodges, N.M. Komerath, D.A. Peters, G.A. Pierce, J.V.R. Prasad, L.N. Sankar, J.C. Wu

Research Engineers: C.M. McKeithan, C.M. Wang

Post Doctoral Fellows: S.G. Liou , and P. Sriram

Graduate Research Assistants:

Ph.D.: Y. Chung, P. Fawcett, R. Funk, D. Gillam, L. Gummadi, N. Hariharan J. Higman, D. Hixon, G. Kim, J. Kim, M. Lal J. Li, J. Leitner, M. Mittal, D. Palmer, W. Park, M.T. Patterson, D. Reece, S. Savanur, X. Shang, W. Stumpf, F.L. Tsung, N. Weston, C. Won, X. Xiao, J. Zhang.

M.S.: J. St.-Angelo, S. Foley, M.K. Lal, G. Nichols, M. Petroski, and B. Zhao

CONTRIBUTED TO PROJECT, BUT WERE NOT SUPPORTED

Faculty:

Prof. V.L. Berdichevsky

Post Docs:

A. Atilgan V. Sutyrin,

Ph.D. Students:

C.E.S. Cesnik, M. Cibulka, Major W. Lewis, and T. Smith,

M. S. Students:

T. Bowles, D. Boyd, P.W. Cheang, Captain S. Ingalls, B.D. Palmer, 1Lt D. Troutman, and Captain D. Wheelock

DEGREES AWARDED (THIS REPORTING PERIOD)

NAME	DEGREE -	DATE	LAST KNOWN AFFILIATION
D. de Andrade	Ph.D.	SEP 92	Post Doc - Georgia Tech
P.A. Fawcett	Ph.D.	SEP 92	
S.M. Foley	M.S.	SEP 92	
J. Leitner	M.S.	SEP 92	Ph.D. Program, Ga. Tech
W.D. Lewis	Ph.D.	SEP 92	AATD, Ft. Eustis, VA
D.S. Reece	M.S.	SEP 92	Ph.D. Program, Ga. Tech
W.M. Stumpf	Ph.D.	SEP 92	Post Doc - Georgia Tech
Y. Chung	M.S.	DEC 92	Ph.D. Program, Ga. Tech
M. Petroski	M.S.	DEC 92	Ph.D. Program, Ga. Tech
L.N. Gummadi	Ph.D.	DEC 92	Post. Doc. Georgia Tech
J. Li	Ph.D.	DEC 92	

RESEARCH TASKS

I. Aerodynamics

Task 1. Studies in Three-Dimensional Viscous Aerodynamics

J.C. Wu and C.M. Wang

Problem Studied

A numerical approach based on vorticity-velocity formulation and an integral representation of the velocity vector has been developed in the past by the present researchers for the study of complicated flow problems. Many 2-D flows including dynamic stall of airfoils can be accurately predicted by the approach. The present phase involves two distinct efforts. The first effort focuses on the extension of the numerical approach to 3-D incompressible flows. The second effort is the development of the method for compressible flows.

Progress During the Last Reporting Period

The extension of the present method is not staightforward. The major difficulties include: 1. accurate determination of the vorticity on solid surfaces; 2. satisfaction of the divergence-free condition for the vorticity field (where the vorticity vector has three distinctive components); and 3. accurate determination of the surface pressure. These issues have been successfully resolved in the present phase. Flows around flat-plate and rectangular wings of NACA 0012 section have been computed by the extended method. Solution of the flat-plate wing has been presented in an AIAA paper (91-3262) and will not be included here. Solutions of the wing of NACA 0012 section with rounded tip are briefly discussed as follows.

Flows of three angles of attack (5°, 15° and 25°) have been computed on a rather coarse O-O grid of 41 X 12 X 31, where the three numbers denote the grid number in chordwise, spanwise, and normal direction respectively. For the angle of attack 5° case, flow is totally attached and the tip vortex is rather weak where the vortex is attached and wrapped around the wing tip before it leaves the trailing edge. The tip vortex becomes stronger for the 15° case, but the vortex is still attached fully on the wing tip. However, large chordwise flow separation is observed on the upper surface and the reversed flow region is diminishing toward the tip. The particle trace plot near the upper surface indicates an eye-type pattern is formed which has also been observed in wind tunnel testing. For the 25° case, the strong tip-vortex lifts off from the tip near the 60% chord and sectional lift shows a hump near the tip caused by the lift-off. Flow separates from the wing leading-edge for most of the span.

The compressibility effect is addressed in the second effort of the present phase. This effect is accounted for by the use of decomposition of the velocity vector in a Helmholtz manner. The rotational part of the velocity can be solved by the present incompressible vorticity-velocity approach whereas the irrotational part is only of limited size (comparable to the vortical region), compared to the solution domain of a full compressible flow solver. The hybridization of the incompressible Navier-Stokes solver and the modified Euler Solver Offers advantages in computational efficiency and accuracy.

Numerical results of flows around circular cylinders and airfoils show excellent agreement with experimental results over a rather broad Mach number range. However, no strong shocks can be treated at the present time.

The detailed mathematical and numerical formulations of the present efforts as well as the numerical results and discussions will be included and elaborated upon in the following upcoming Ph.D. theses:

1. Kim, G., *A Vorticity-Velocity Approach for Three-Dimensional Unsteady Viscous Flows over Wings,* Ph.D. Thesis, Georgia Institute of Technology, in preparation.
2. Ping, Q., *Computation of Flows Around Oscillating and Fast Pitched Flat Plates,* Ph.D. Thesis, Georgia Institute of Technology, in preparation.
3. Patterson, M.T., *An Integro-Differential Solution Methodology for Compressible Rotational Flows*, Ph.D. Thesis, Georgia Institute of Technology, in preparation.

Task 2. Aerodynamic Interactions

P.I.: Dr. N.M. Komerath
Research Team: Robert Funk, Jai-Moo Kim, Shiuh-Guang Liou

Objectives

This task seeks to advance capabilities and knowledge in the area of aerodynamic interactions in rotorcraft flows.

Progress during the final period: 7/92-1/93

The effort during this period was concentrated on vortex-surface interactions and vortex-shear layer interactions. Jai-Moo Kim's dissertation is to be defended in mid-February. Papers have been accepted for presentation at the AIAA Fluid Mechanics conference on vortex-surface interactions (joint work with Prof. Conlisk's group at OSU), spatial correlation velocimetry in the rotor wake, and summarizing the behavior of the rotor wake around the airframe. The results obtained in this period are summarized along with the final contract summary below.

Summary of achievements during the 5-year contract period

1. Rotor Wake / Airframe Interaction

A good definition has been obtained of the interaction between the vortex-dominated wake of a rotor and the flow over an airframe. For the case where there is no large-scale separation of the mean flow, a final piece of the puzzle came recently when J.M. Kim showed the important role of the core axial velocity in explaining the asymmetric vortex behavior, and discovered the remains of the tip vortex below the airframe. Now we can provide guidance to those computing the wake/airframe interaction on what to do with the vortex near the airframe.

The presence of separated mean flow was found to be surprisingly simple to model (Kim, thesis '93). At the low advance ratios where wake/fuselage interaction is strong, it was found that the vorticity in the separated shear layer was relatively weak, so that the tip vortex totally dominated the flow behavior. It appears that the separated region can be reasonably modeled by a weak recirculation zone bounded by a vortex sheet. The tip vortex suffers little modification in passing through this zone, and the vortex/airframe interaction proceeds in a similar fashion to the case without mean flow separation. The separation zone, on the other hand, is periodically destroyed and re-established. We anticipate that the dominant features of the surface pressure can be captured by simple models without resort to Navier-Stokes formulations. Of course, there are several secondary features that need further examination, especially with regard to the possibility of flow control exploitation.

2. Vortex-surface interaction

The interaction of a vortex with a curved surface remains as the dominant problem needing detailed experimentation and analysis. Progress was made in achieving excellent correlation between calculation (OSU) and experiments up to the stage where the vortex core started interacting with the surface boundary layer. In the last reporting period, a concerted effort was made, with Prof. Conlisk present to provide guidance, to visualize the initiation of boundary layer separation upstream of the vortex. After 2 days of intensive efforts, several frames of video were obtained using an intensified camera showing clear separation patterns, captured with a temporal resolution of 25 nanoseconds.

3. Rotor Wake Geometry

Kim's finding of the concentrated roll-up of the inboard vortex sheet explained some of the "secondary" vortex features previously observed by Liou and Brand. Kim's subsequent experiments clearly showed that the roll-up was greatly accelerated by interaction of the sheet with the tip vortex from the following blade. In fact, the subsequent vortex trajectory, and thus the "skewing" and "contraction" of the near wake, are bound to be influenced by this counter-rotating vortex to a higher degree than by mutual interaction between tip vortices. This was an unexpected finding, which originated in a disagreement between a Ph.D. candidate and his advisor, followed by the candidate undertaking his own experiments to prove his point beyond doubt.

4. Spatial Correlation Velocimetry

The high-speed planar velocimetry effort, undertaken as a high-risk exploration in 1988, has succeeded, and is producing a unique capability. An unexpected bonus is the feasibility of application to large-area measurement without lasers. Also, since the technique works without phase-averaging, we see the way open to undertake much more challenging explorations of turbulent phenomena. During the final period, Philip Fawcett succeeded in capturing a large number of instantaneous velocity fields in the wake of an isolated rotor in forward flight. A paper based on these results has been accepted for presentation at the Fluids & Plasma Conference in July '93. A U.S. Patent application based on this technique has been approved, and is in the final stages of revision of figures.

5. Multi-Diagnostic Capability

The phase-resolved point measurement techniques, the desynchronized visualization technique, and SCV have come together in a multi-faceted measurement capability, which opens the way for experimental research on complex configurations during maneuvers. The first demonstration of the power of this approach came in our study of wake/wing interaction (Susan Foley, M.S. Special Problem and AIAA 92-4008), which revealed unexpected phenomena related to flow separation and reattachment. While the individual pieces may appear mundane, the order-of-magnitude increase in the productivity of advanced diagnostic techniques has profound implications for the feasibility of studying many interaction problems.

Task 3. Blade Tip Aerodynamics

Problem Studied

The objective of this research is to understand the behavior of the flow over rotor tip shapes for use at high pitch angles, and to develop methods of improving retreating-blade performance in forward flight.

During the past five years of research effort, much progress was made under this task. The work performed under this project has been documented in open literature. Several joint studies and publications with researchers in the U. S. Helicopter industries were also carried out during this period. A list of all publications under CERWAT support for the period October 1987- October 1992 is enclosed.

Some of the major accomplishments during this period are as follows:

1) The 3-D Navier-Stokes solver developed under the original CERWAT program has been continually updated to improve its speed, and accuracy. We have replaced the second order accurate finite difference formulas in this solver with fourth order accurate operator compact forms. The original numerical viscosity terms in this solver have been replaced with a scheme based on the Roe upwind scheme. The Baldwin-Lomax turbulence model has been replaced with a k-e turbulence model. For hover and quasi-steady forward flight studies, the CPU time needed has been reduced to less than 1 hour on the Cray Y/MP class of computers (for a 120,000 point grid) through local time stepping and replacement of the block tri-diagonal matrix inversions within the flow solver with scalar tri-diagonal matrix inversions.

2) The 3-D Navier-Stokes solver was applied to advanced rotor blade tip shapes. A Georgia Tech tip shape, and a BERP-like tip were studied. Where possible, comparisons of the velocity field were made with the measurements carried out by Prof. Komerath We also studied the effects of blade rotation on the flow over the blade tip, by computing the flow over the BERP-like planform in the fixed wing mode and rotary wing mode. It was found that the centrifugal flow effects in the rotary wing mode had a significant beneficial effect on the rotary performance particularly at high collective pitch settings.

3. We coupled the 3-D unsteady Navier-Stokes solver with an unsteady full potential flow solver to arrive at a hybrid solver which solves the computationally costly Navier-Stokes equations only in the small viscous region surrounding the blade. Elsewhere the inexpensive potential flow formulation is used. The formulation is fully three-dimensional, can handle unsteady compressible flows with embedded shock waves, and can model the effects of turbulence.

4. Many of the 2-D and 3-D analyses have been modified to perform aerodynamic design of airfoils and rotor blades as well. We have made the computer codes for airfoil design available to researchers at McDonnell Douglas Helicopter Co. (Dr. Ahmad Hassan), Bell helicopter Textron (Jim Narramore) and Sikorsky (Bob Moffitt).

5. During this period, we closely worked with other Georgia Tech researchers on interdisciplinary applications. A 3-D unsteady panel method, that incorporates Dr. Hodges' curved beam theory was developed and used to predict the lead lag damping characteristics

of rotor blades in hover. We worked with Dr. Prasad on the development of 2-D and 3-D unsteady analyses that predict the effects of control surface motion on the rotor blade acoustics and vibratory airloads.

Experiments

Team: N.M. Komerath, S-G. Liou, and Matt Petroski

During the final period, Petroski wrote up results for submission to the AIAA Fluids conference, and prepared a paper for the Lichten Award Competition placing his results in the context of our previous results, CFD results, and previous work on both helicopter blades as well as propellers at high pitch angles. A discussion has been initiated with researchers at NASA Ames (Peter Talbot and Chee Tung) on the general observation that propeller blades demonstrate apparent lift coefficient values far in excess of their predicted stalling values under steady rotating conditions.

Summary of 5-year project

The experimental portion of this task set out to study the flowfield around a complex blade tip geometry operating at high pitch angles. This was an experiment designed to assist computational research, not to model full-scale phenomena. Thus, the tip model was fabricated using the surface coordinates used in the Navier-Stokes computational effort. A single-bladed rotor was used, with a simple inboard geometry. The operating Reynolds number was moderate, within reach of current computational resources.

Initial experiments documented the behavior and trajectory of the tip vortex. The velocity field was then measured using LDV, at low and high pitch angles. The results were compared directly to CFD results and presented in a 1990 AHS Forum paper. The rotor experiments were then extended, and the rotor blade was then used as a fixed wing in the wind tunnel at a freestream speed corresponding to the tip speed. Velocity measurements and laser sheet visualization were then used to compare flow separation characteristics and spanwise velocity behavior between the fixed-wing and rotor cases. This was a unique experiment, and provided results that supported the importance of centrifugal effects in the rotor flow field. The results were presented at the AIAA Aerospace Sciences Meeting in 1991, and were controversial. Subsequently, both the rotor and fixed-wing experiments were extended to obtain velocity field with finer grid resolution near the blade surface, and to obtain more data inboard. The flow visualization was also extended using a new smoke generator. This provided a surprising benefit: the seeding condensed and deposited on the rotating blade surface in the regions of stagnant and recirculating flow. The resulting surface flow patterns provided excellent correlation with velocity field results on the surface flow behavior. The fixed wing experiments were also repeated, with the freestream velocity corresponding to the tip speed, but the angle of attack matched to the effective rotor angle of attack, correcting for the measured inflow velocity. These experiments provided clear visual evidence of the "inboard notch vortex" that appears to control flow separation on the tip at very high pitch angles. The results again proved that flow separation is greatly reduced under rotating conditions for the same angle of attack. The issue of centrifugal pumping remains unresolved: hypotheses about the unambiguous effects of centrifugal pumping on the measurable velocity field could neither be confirmed nor rejected based on the measurements obtained.

This task made significant contributions to our measurement and visualization techniques. The copper vapor laser was made operational and used first to visualize the vortex structure from the complex blade tip, and examine the reasons for the observed unsteadiness of the tip vortex trajectory. The initial experiments to examine the concept of Spatial Correlation Velocimetry were also performed here. The wax deposition method of surface flow visualization on a rotor blade was observed here, and is expected to find extensive use. We anticipate strong interest in the problem of rotor flow at high pitch in future. The "Himmelskamp effect", where propellers and windmills have been found to operate at section lift coefficients well above predicted stall under steady conditions, is attracting interest at NASA Ames (Peter Talbot, Chee Tung), and we anticipate increased collaboration in this area.

II. Aeroelasticity

Task 1. Unsteady Aerodynamics for Rotor Aeroelasticity

D. A. Peters and D. H. Hodges

Problem Studied

Rotor aeroelastic response and stability analyses have traditionally been carried out in terms of modern nonlinear structural dynamics models but with relatively crude, quasi-steady aerodynamics. For the hovering flight condition this combination is generally stated to be adequate, although without proof. In forward flight, however, it is generally recognized that this type of formulation is severely limited. Incorporation of nonlinear, unsteady, free-wake analyses based on panel methods into such codes by presently known techniques requires the introduction of hundreds or even thousands of state variables and has not been attempted. On the other hand, relatively sophisticated performance codes have existed for some time that make use of three-dimensional lifting surface and panel methods for determining the effects of tip shape, sweep, etc. on thrust and performance. However, such codes generally do not include the effects of blade aeroelastic deformations. It is clear from existing lifting line analyses that do include these effects that they could have a significant influence on the accuracy of calculated damping. Alternatives to complete free-wake analysis include the dynamic inflow theory of Peters and co-workers in which the induced inflow distribution is expanded in terms of an arbitrary number of radial functions and azimuthal harmonics. Another is the reduction of the number of aerodynamic state variables in the analysis by expansion of the discretized wake parameters in terms of a relatively small number of functions and applications of some variant of the weighted residual technique.

Progress During the Last Reporting Period

a) Hovering Stability and Inflow

Our correlations between theoretical damping predictions and the Army damping measurement (Sharpe, Ormiston, et. al.) have been greatly refined and improved. First, we have revised the lift-curve slope and drag data used by previous investigators (and by us) through the use of NACA tables at the Reynolds Number of interest (600,000). This change has improved damping by 25%. Second, by comparing measured reduced flow (as given by Sharpe) and comparing with predictions from momentum theory, our inflow model, and our panel code, we have determined that there was significant recirculation in the test chamber; and we have modified our results to reflect this. Third, detailed comparisons of calculated and measured frequencies have indicated that the torsional flexures in the test model contributed to the inplane bending flexibility. Although the percentage change is not large, the inplane frequency is very near 1.5/rev; and inflow coupling is significantly affected by whether or not the frequency is greater than or less than 1.5. These last two refinements gave another 25% improvement.

It is interesting to note that the key to making us look more deeply into static inflow and flexure stiffness came from the power of our finite-state model. In particular, we noticed that the theoretical collective-mode damping agreed better with measured differential-mode damping than did the theoretical differential-mode numbers. We then looked at the magnitude and phase of the "lift eigenvectors". (Recall that, since inflow is represented by states, eigenvector information contains aerodynamic as well as structural information.) The information in the lift eigenvectors led us to believe that small changes in frequency about 1-5/rev as well as small changes in static inflow could account for the damping differences. This proved to be true. The results of this latest correlation will be presented at the 49th Annual Forum of the AHS.

b) Forward Flight

Our forward flight work was essential completed at the last reporting period. We will present a paper on the results at the coming AIAA/AHS DM Conference in San Diego, April 19-21.

External Interactions

We continue to work with Dr. Robert Ormiston of the Army Aeroflightdynamics Directorate. In addition, we have had new interactions with workers at Michigan State and with the Georgia Tech Flight Simulation Lab. Finally, this inflow model is being incorporated in 2GCHAS.

Task 2. Vibration and Trim of Elastic Rotor Blades with Dynamic Stall

D. A. Peters

Problem Studied

In this task, we have been studying the effect of dynamic stall on rotor trim, on rotor vibrations, and on our ability to compute these successfully. This work has two foci. The first is on development of good analytic models of the stall mechanism. In this area, we began with the ONERA model and have been making many modifications to it, most of which have been adopted by the French also. The second focus is on efficient trim methodologies. In this area, we have worked hard on harmonic balance techniques, periodic shooting, and autopilots.

Progress During the Last Reporting Period

We have re-visited our dynamic-stall model to study exactly how it behaves when coupled with our finite-state inflow model. Unfortunately, however, our inflow model is 3-D, whereas all of the dynamic stall data are 2-D. Thus, we first had to develop a 2-D version of our finite-state inflow model. This was done under a grant from the Army Aeroflightdynamics Directorate (Robert Ormiston, Technical Monitor). We have now coupled this 2-D inflow model with our latest version of dynamic stall, and this is giving excellent data correlation.

In trim methodologies, we have yet to couple successfully periodic shooting and autopilot in a hybrid scheme. However, pure shooting and pure autopilot are both mature and are being applied in aeroelastic analysis packages at NASA Langley Research Center and here at CERWAT/CERT for optimization applications.

External Interactions

We have worked with NASA Langley, NASA Ames, the University of Sao Paulo, Advanced Rotorcraft Technology, Inc., and the Washington University group. Advance Rotorcraft Technologies is putting our dynamic stall model into their simulation programs.

Task 3. Unsteady Aerodynamic Testing of Model Rotors

G. A. Pierce, N. M. Komerath, and S.G. Liou

Problem Studied

This task is intended to identify the relationship between the inflow velocity field in the vicinity of a helicopter rotor blade and the associated blade pressure distribution for conditions of dynamic pitch control. An experimental investigation forms the basis of determining this relationship between dynamic inflow and unsteady airloads. Tests conducted in the AeroTech facility with a model rotor blade consist of two complementary investigations. The first entails the measurement of absolute pressure distributions on the blade surfaces, while the second involves laser velocimeter measurement of the inflow velocity field in the region immediately above the rotor disk. Recorded synchronization of these measurements with respect to the dynamic pitch control and azimuthal position permits their correlation with each other and subsequent identification of their interrelationship

5-year Summary of Progress: Experiments

This Task sought to measure the time-varying inflow to a rotor excited in pitch, and the associated effects on the surface pressure field. A two-bladed rotor was used in hover, with pitch excitations driven by hydraulic actuators using digitally-specified 4-per-rev harmonic waveforms. The inflow velocity field was measured using LDV, and the surface pressure fluctuations were measured using surface-mounted Kulite absolute pressure transducers. Several major problems were encountered and solved. Some of these were: acquisition of velocity data in a large facility with high enough data rate to capture the detailed waveforms of a flowfield excited at 40Hz; resolving the perturbations due to a pitch oscillation of 1 degree amplitude in a periodic flowfield with large-amplitude fluctuations; calibration of surface-mounted absolute transducers to enable measurement of extremely small pressure changes; transmission of data from extremely low pressure perturbations from the rotating system; absolute synchronization of the systems for pitch excitation, velocity data acquisition, and, later, pressure data acquisition, and later, digital correction of the pitch excitation waveform for the complex transfer function of the excitation system.

The experimental results are summarized in two papers submitted to the AHS Journal; a third paper is in preparation dealing the correlation of the pressure and velocity results with analytical methods. In addition, the velocity field results have been used by Prof. Peters in correlation with his model for dynamic inflow, with excellent success. This correlation has recently appeared in the Journal of Aircraft. Primary conclusions from the velocity field experiments are:

Data rates over 4000 sec-1 have been achieved in backscatter in a large rotor test facility. The scatter in individual time history plots is minimal, indicating uniformity of seed particle size, freedom from particle lag effects, and that phase-averaging is not essential. Agreement of the steady-blade data with analytical results demonstrates that facility flow recirculation errors are insignificant, and accurate phase synchronization is achieved. The 4 per rev inflow variation is substantial, even for 1-deg. oscillation amplitude. The variation depends on excitation phase, and is relatively insensitive to the blade position. The inflow response to pitch excitation decreases in amplitude near the blade tip. The unsteady inflow variation over the rotor disk was successfully synthesized assuming axial symmetry. Substantial phase lag effects are seen in the flowfield. The dynamic inflow variation reveals substantial hysteresis, implying that the flow is totally unsteady. However, the unsteady shedding vorticity can be treated with a quasi-steady approach, if the phase lag has been taken into consideration. While the hysteresis has a radial variation, it is not driven by tip effects.

The conclusions from the pressure field measurements are:

At a fixed radial and chordwise location, a 180° phase shift between upper and lower surface pressure data is seen even at low amplitudes of pitch oscillation. Instantaneous perturbation pressure repeats periodically with rotor azimuth angle, as expected. The upper and lower surface perturbation pressure amplitude profiles remain close to each other and converge towards the trailing edge. Even at fixed mean pitch angle, two distinct cases exist for the study of wake dynamics, depending on the phase between individual blade motions and thus on the number of blades and n, the harmonics of the forcing frequency. At a fixed radius, amplitude of lifting perturbation pressure increases with the reduced frequency, except at 3-per-rev and 5-per-rev where large increase occurs due to phase effect. The chordwise distributions of the phase rotate and become steeper with reduced frequency. The reduced frequency decreases as we go outboard. At fixed test conditions, lifting pressure amplitude decreases outboard. The phase profile rotates and becomes flatter. The above two effects become more pronounced with increasing reduced frequency. At high reduced frequency, satisfaction of Kutta condition becomes sluggish. Increasing mean pitch increases wake spacing and affects the unsteady pressure amplitude near the leading edge. The amplitude first increases and then decreases with increasing mean pitch and the phase angle distribution becomes flatter. At the blade tip, as higher pitch is reached, the loss is sudden and severe.

III. Structures

Task 1: Nonlinear Beam Theory

D. H. Hodges

Background:

Many existing helicopter blade analyses, including that of the Army's 2GCHAS program, are based on simplified beam theories, such as that of Hodges and Dowell (1974). Inherent restrictions in such analyses that are inappropriate for realistic rotor blade configurations include:

(1)The equations are restricted to moderate rotation theory which, for certain problems such as bearingless rotor flexbeams, is inadequate.

(2)They do not treat initial curvature and, although they were derived to treat initial twist, the derivation is not based on kinematics appropriate for curvilinear coordinate systems.

(3)They do not account for material anisotropy, shear deformation, or warping, all of which are essential for composite blade modeling.

(4)They are based on a Green strain formulation which produces many superfluous terms in the equations of motion. Based on past *ad hoc* methods of simplification (such as ordering schemes), removal of these terms is not straightforward nor does it result in practical simplifications, since the resulting equations fill several pages.

Originally we set out to overcome these problems, and we believe that we have achieved this and more. Some aspects of our theory are quite mature now, and others are in the final stages of being developed. Still others are beyond the scope of the present project and must be developed under the auspices of separately funded projects. Also, further validation needs to be done, much of which remains in planning stages because earlier graduate research assistants were lost through the Ph.D. qualifying exam.

Summary of Theory Developed to Date:

The work accomplished to date has led to a modular theory which we view as ideal for rotor blade modeling as well as for other applications. Our theory is based on a decoupling of the sectional analysis (to obtain elastic cross-sectional properties) from the global deformation analysis.

Berdichevsky (1981) appears to be the first in the literature to show that consistent application of the variational-asymptotical method to the equations of *three-dimensional* geometrically nonlinear elasticity for beams leads to two simpler problems: *a linear, two-dimensional* cross-sectional analysis, from which the sectional properties can be calculated, and *a nonlinear, one-dimensional* beam analysis which uses those properties in calculation of the beam deflections, rotations, etc. The sectional analysis also yields a set of influence functions which can be used to calculate the three-dimensional stress, strain, and displacement throughout the beam once the one-dimensional problem is solved.

Accordingly, we have constructed our theory in a modular fashion with four parts:

(a) *exact*, nonlinear, kinematical equations for beam displacements and rotations in terms of intrinsic strain measures (stress resultants do not appear in these equations);

(b) *exact*, nonlinear, intrinsic, global equilibrium equations in terms of physical stress resultants and intrinsic strain measures (displacement and rotation variables do not appear in these equations);

(c) asymptotically correct constitutive equations which relate the physical beam stress resultants (section force and moment measure numbers) to the intrinsic strain measures (displacement and rotation variables do not appear in these equations);

(d) influence functions which give asymptotically correct expressions for all three-dimensional displacement, strain, and stress variables in terms of one-dimensional intrinsic strain measures (one-dimensional stress resultants, displacement and rotation variables do not appear in these relations).

The first three modules of the theory can be combined to form a single mixed variational statement in space-time, described in detail by Hodges (*International Journal of Solids and Structures*, 1990). All four parts must account for initial curvature and twist. In- and out-of-plane St.-Venant warping is a by-product of (c) and is used to find (d); however, no warping variables appear in any of the final equations. Parts (a) and (b) along with the results of (c) constitute a closed theory which can be put into a very compact form without the necessity of ordering schemes or other approximations. Part (d) is used for obtaining the complete displacement field and the strain or stress field throughout the beam once the equations in (a) — (c) are solved. Certain aspects of parts (c) and (d) are complete, but some are still under development.

It should be noted that treatment of the restrained warping requires additional variables of all types. This is very much analogous to modeling a flexible body with rigid-body modes and flexible modes, the St.-Venant solutions being analogous to the rigid body modes. The edge-zone behavior is governed by higher-order deformation modes of the section, very much analogous to higher-frequency modes in deformable bodies. The treatment of edge-zone phenomena and high-frequency dynamics must be regarded as coupled, as previous work has shown. Primarily because of its complexity, further development on this aspect of the problem is outside the scope of the present project. A separate proposal for research on this subject has been written by Dr. V. L. Berdichevsky (one of the leading authorities in the world on this subject) and the P.I. and submitted to the ARO.

Constitutive Equations and Influence Functions (Cesnik):

Motivation: All the present work is being devoted to developing a practical, computationally efficient method to extract the elastic cross-sectional properties of an anisotropic beam with arbitrary cross-sectional materials and geometry. The most systematic framework to our knowledge is the variational-asymptotical method of Berdichevsky. This analysis methodology is able to provide the asymptotically correct influence functions, allowing us to express the three-dimensional field variables in terms of one-dimensional generalized strain measures. This means that for arbitrary nonlinear deformation of anisotropic beams, we are able to determine the displacement, strain, and stress throughout the beam. Published work prior to ours which applies this method to beams does not consider the generally anisotropic beam beyond the first approximation (classical theory for bending, torsion, and extension), nor are these methods developed into computational methods developed to calculate the elastic constants. Indeed, there is a long way between the mathematical theory and a practical computational methodology for realistic rotor blade structures.

Accomplishments: We developed the equations for the first approximation for anisotropic beams section constants and programmed for solution by using the finite element method to discretize the beam cross section. A finite element code was written to evaluate the warping and the stiffness matrix for a beam cross section comprised of laminated orthotropic materials in which the fiber direction is arbitrary. *Note that our analysis is not restricted to beams which have sections of any particular geometry (such as thin-walled).* The element used is a four-noded planar rectangular element with three degrees of freedom per node. Element matrices are formulated by exact integration using *Mathematica* (a symbolic manipulation program). The code is quite portable and can be run on desktop computers such as PC's and Macintoshes. It is referred to as VABS (*V*ariational-*A*symptotical *B*eam *S*ectional) Analysis.

Progress During This Reporting Period: In this reporting period we have extended the previous work to include the first-order effects of initial curvature and twist. The warping in this case has two parts: the first is the same as that for the prismatic case and the second is a first-order correction to account for initial curvature and twist. The corrected warping can be used to find accurate three-dimensional displacement and strain fields within the beam, but the correction of the warping is not needed to find the elastic constants. The theory is such that the only static coupling between these new degrees of freedom and the existing six is elastic, i.e., in the constitutive law. The theory for initial twist and curvature was reported in papers at SECTAM and DM. Numerical results obtained to date show a quadratic convergence rate against the number of elements.

Future Work: Our present element is not sufficient for realistic blade modeling, and plans are being made to expand the element library to include isoparametric elements, which treat curved airfoil surfaces more accurately than the present method can. We also are making an effort to improve the computational efficiency of the method. There are several instances in which certain mathematical transformations which are appropriate for analysis (to obtain a well-posed minimum principle, for example) are not necessarily the best ones to use in computational algorithms.

In the process of extending our theory and code to account for initial curvature and twist, a great deal of progress was made in developing a framework for incorporating degrees of freedom other than the six rigid-body translational and rotational degrees of freedom for the cross section now treated. This would be important for situations in which the warping must be restrained, such as in bearingless rotors. The theory is such that the only static coupling between these new degrees of freedom and the existing six is elastic, i.e., in the constitutive law.

Validation (Reece):

Another aspect of our research calls for the validation of the cross-sectional analysis. We have now compared our numerical results with data from composite beam experiments done at Massachusetts Institute of Technology and at the University of Maryland. Our own experimental work is progressing slowly. Rather than duplicate what others have done, the focus of our work will be to address whether spanwise nonuniformity significantly affects the elastic constants, starting with the isotropic case. Our first experimental results should be available during the next reporting period, if all goes according to present plans.

Numerical Work (Chung and Shang):

In order to apply (a), (b), and (c) efficiently, it is necessary to take advantage of the sparsity of the coefficient matrices and to try to optimize sparsity by choice of shape functions. To date all our nonlinear finite element work has centered on the use of the weakest form of the equations and the crudest possible shape functions. In this approach numerical element quadrature is not necessary if the properties and forcing functions are integrable functions. However, for non-uniform beams we do not know whether it is necessary to integrate the properties exactly or if it would be just as accurate to approximate them as piece wise constant to go along with the shape functions. This has a direct bearing on how one approaches development of *p*-version finite elements in the nonlinear case. We know that these elements perform very well relative to the crude approach if the element properties are constant, the forcing function is constant, and the problem being treated is linear. Although what happens in the general case is still being studied, we have now established that higher-order elements do improve the accuracy significantly for beams with constant and linearly varying properties. The next step is the examine what happens when numerical quadrature is used instead of exact, and to go through the same process for a nonlinear problem. Further unanswered questions reside in the treatment of time-domain issues. How does one ensure numerical stability in time-marching algorithms for mixed models of beam dynamic behavior? We view this as outside the scope of the current project and plan to address it later under the auspices of a new project.

Related Research

Our work has been applied to the dynamics and aeroelastic stability analysis composite rotor blades in hover under other ARO-sponsorship; this activity is in a no-cost extension and will end in September 1992. Our model appears to be well-suited for low-frequency aeroelastic stability analysis. Our work to extend apply similar methodology to laminated plate behavior is being funded by the Army Aerostructures Directorate at NASA Langley Research Center. Our being able to work these problems in parallel has been extremely beneficial.

External Interactions:

with Drs. Robert A. Ormiston and Gene C. Ruzicka of Aeroflightdynamics Directorate concerning GRASP and 2GCHAS (PI spent three weeks at AFDD during Summer 1991)

with Dr. Charles Rogers, Dr. Gene Sadler and Mr. Mark Dreier of Bell Helicopter concerning finite element modeling of rotor blades

with Prof. Larry Rehfield, University of California, Davis concerning extension of his sectional analysis theories and their application to specific configurations

with Dr. T. Kevin O'Brien and Mr. Howard Hinnant of the Army Aerostructures Directorate and Dr. Alexander Tessler of NASA Langley concerning laminated plate problems

Task 2. Deleted

Task 3. Rotorcraft Vibrations and Structural Dynamics

S. Hanagud and J. I. Craig

Problems Studied

As a part of this task, we conducted research in two different but related areas of structural dynamics. The subject matter of the first part was smart or adaptive structures. The subject matter of the second part was structural dynamic system identification.

SMART STRUCTURES

Smart structures can be defined as a class of structures that have built-in adaptive capability and/or intelligence. Such an adaptive capability or intelligence is used to optimize the performance of a structural system to changing environments. The subject matter is an interdisciplinary field. In our experience, the research has involved a combination of the fields of structural mechanics, control, fluid mechanics, and mathematics. The research has been both theoretical and experimental.

Vibration Control

Our work started during the second year of the first phase of CERWAT. We initiated the work on mathematical modeling and optimum vibration control of beams with bonded piezoceramic sensors and actuators. We followed this work with smart structural designs that can provide robust control. The robustness was provided to account for some debonding of sensors and delaminations that would alter the stiffness and differential equations of the model. We developed the needed equations. Controllers were designed by using H-infinity and Mu-synthesis techniques. We have also developed techniques to control nonlinear vibrations. A first phase of experiments to control nonlinear vibrations is being developed.

Smart Structures in Higher Harmonic Control

We have completed a feasibility study in this area. The objective of the feasibility study was to reduce vibrations at selected locations of an airframe of a rotorcraft by the use of smart structures concepts. The usual higher harmonic control considers a reduction of n-per-rev oscillatory loads transmitted to the airframe from the rotor system. In our work, we have used distributed sensors and actuators in the airframe and an H-infinity controller to control higher harmonic components of vibrations at selected locations of the airframe. We are also studying a combination of rotor mounted systems and airframe mounted sensor/actuator system to optimally reduce vibrations at selected locations of a helicopter.

Smart Structures in the Health Monitoring of Structures

An important application of smart structures is in the area of health monitoring of structures. A typical health monitoring system should be able to identify the damage when it occurs and then automatically control the growth of damage. We have completed a feasibility study of delamination detection and control of delamination growth. In th:, feasibility study, the delamination detection technique is based on the observed change in the dynamic response of a delaminated structure. The automatic control of the growth of the delaminations is accomplished by reducing the magnitude of interlaminar stresses by using the concept of smart structures and a control moment feedback. Our next step will be the validation of our work. We have experimentally completed a first phase of the validation of delamination detection.

Adaptive Airfoils and Smart Structures

The ability to actively change the shape of an airfoil section, while it is in motion, has been the dream of many aerodynamicists, dynamicists, and control engineers for years. At Georgia Tech, we have developed four concepts to make such active changes in the airfoil shape. Our first attempts were based on the use of shape memory alloys. We were able to get large leading and trailing edge deflections by the use of shape memory alloys. However, because of the needed heating and cooling cycles, we had difficulties in obtaining the needed frequency responses. This difficulty has been resolved and we are now in the process of developing a two bladed rotor system.

As a next step, we have used piezoelectric stacks to obtain flap-motion in the range of 3-10 Hz. This is based on a cantilever beam actuation. Angles in the range of 2 to 5 degrees have been achieved. We are now studying methods of using piezoelectric actuators to achieve higher frequency ranges and larger angular deflections without the use of the cantilever beam concept.

We have also theoretically studied the use of adaptive airfoils in actively controlling the blade-vortex interaction. During the operation of a rotorcraft, rotor blades interact with vortices shed by preceding blades. As a result of the interaction, large pressure pulses are created at the leading edges of the airfoil. We have shown the feasibility of reducing the magnitude of these large pressure pulses by the use of adaptive airfoils. We have used smart actuation to change the camber of the airfoil and optimum control techniques to reduce the pressure magnitudes. Work is continuing in this area under a SBIR with the U.S. Army AFDD at Ames Research Center.

Jitter Vibrations in Rotating and Pointing Systems

The concept of smart structures has also been implemented for the jitter vibration reduction of flexible pointing and rotating systems. Tracking a desired trajectory using flexible rotating and pointing systems is a nonlinear control problem due to the combined effect of large rigid body motions and small flexible body motions. Smart structures concepts have been used in the form of distributed sensors and actuators to reduce jitter vibrations caused by the flexible body motions. Hanagud, et. al. used piezoceramic sensors and actuators for this jitter reduction application.

Micromotors as Smart Actuators

Actuators of miniature size are called micromotors. Micromotors are either electrostatic motors or motors developed using smart materials like piezoelectric materials, electrostrictive materials, shape memory alloys, etc. One of the motivations for the development of micromotors is based on the fact that smaller systems can move small parts much faster than larger systems. Moreover, thermal expansion and vibration problems are minimal when smaller systems are used. In addition, it is easier to obtain high accuracy with smaller systems and because the floor space required is minimal, they can be incorporated at intricate locations without much difficulty.

At Georgia Tech, Allen and his colleagues have developed a novel method of fabricating high aspect ratio electrostatic micromotors. This process used polyimide electroplating forms for the fabrication along with standard commercially available materials. The fabrication process begins with the making of an oxidized silicon wafer substrate coated with a four layer metal system. Chromium is used as the first metal and acts as an adhesion layer. Copper is used for the second metal for plating the stator and pin components of the motor. Again, a layer of chromium is used for metal three for the purpose of protecting the copper coating. This layer of chromium will also act as a release layer for the rotor structure. A layer of copper used for the fourth metal acts as a seal layer for the rotor structures. We have completed a preliminary study to incorporate micromotors as smart actuators.

IDENTIFICATION

The field of structural dynamic system identification has been an active field for the past two decades. However, with the exception of some preliminary work by Meirovitch and his colleagues, there has been very little effort devoted to development of identification techniques that can relate an identified mathematical model to changes in the physical variables and can apply the method to large scale helicopter airframe structural models (AH-1G airframe finite element models). A part of the support for this work was also provided by NASA. Our method is a two-step method and can be designed to consider specific variables like damping constants, dynamic stiffnesses or boundary conditions.

A second area that is of significant interest in helicopter rotor dynamics and structural dynamics is the area of nonlinear system identification. As a part of the first phase of the CERWAT program, we developed a perturbation method for nonlinear structural dynamic system identification. During the second phase, we have developed non-linear structural dynamic system identification techniques on the basis of Hammerstein integral operators. Our method is call the Hammerstein's feedback model for nonlinear system identification. This method has resulted in practical techniques that can be applied to multi-degree-of-freedom systems.

TECHNOLOGY TRANSFER

Our program has included technology transfer with the Army laboratories at Fort Eustis, NASA-Langley Research Center, and NASA-Ames Research Center. We have also worked with Sikorsky aircraft in the areas of structural integrity and the development of smart airfoils. We have worked with Bell Helicopter in the area of structural dynamic system identification.

As a part of the technology transfer program, we have published 27 papers in the area of our research.

Task 4. Damage Resistance in Rotorcraft Structures

E. A. Armanios

Problem Studied

The primary objective of this research is the development of a damage resistance concept in composite rotorcraft and airframe structures by tailoring the microstructure.

Final Report:

This report is an overview of the research performed in this task. It describes the major accomplishments, the lessons learned and the future investigation which stems from its findings.

Damage resistance through microstructural tailoring:

This concept is based on the fact that a given damage mode in laminated composite does not occur in isolation but is often accompanied by other modes. Microstructural tailoring takes advantage of the interaction of the different damage modes to create a resistance behavior. The theoretical basis of this concept was developed in Ref. *1* and its validation was provided by testing ply drop configurations which were designed based on the microstructure tailoring concept. The design was intended to create a resistance to delamination or ply separation, a primary damage mode in laminated composite. Test have verified delamination resistance behavior. The average load at failure relative to the onset of delamination is 1.5. This corresponds to a relative fracture toughness increase of 1.22. Delamination resistance behavior was created by interaction of matrix microcracking with delamination. Evidence of matrix microcracking with delamination growth was provided by scanning electron micrography and synchrotron microradiography [*2*].

The inclusion of an adhesive layer or a resin rich pocket results also in a delamination resistance behavior. A quantitative fractography model [*3*] was developed in order to explain the observed delamination arrest phenomena. The variations in fracture surface morphology, found by the quantitative fractography and statistical analysis, were determined to be caused by variations in the thickness of the interlaminar matrix layer, rather than by events during fracture. The laminates were unidirectional ply drop made of brittle as well as toughened material systems. A simple model has been proposed that explains the arrest phenomenon in terms of one-dimensional model.

Fracture Analysis of Transverse Crack-tip and Free-edge Delamination:

Since the damage resistance concept uses the interaction of damage modes, an investigation of transverse crack-tip and free edge delamination was performed [*4*]. Critical loads and delamination modes were identified and compared with experimental results. Hygrothermal effects were included to make the comparisons realistic. Hygrothermal stresses due to the cure cycle can have a significant influence on the delamination behavior of laminated composites. This was shown in Ref. *5* for the interlaminar stresses and strain energy release rate associated with Mode I free-edge delamination.

The investigation of damage modes in laminated composites has focused on extension loading, however, rotorcraft structures are subjected to combined extension, bending and torsion loads. In order to ensure damage tolerance of rotorcraft structures combined loading effects should be considered. An interlaminar fracture analysis for laminates subjected to combined extension, bending and torsion loads has been developed. This analysis is found to be also applicable to unsymmetrical laminates.

Analysis of Laminated Composites under Combined Loading

An analytical model for laminates subjected to torsion was developed for unidirectional and cross-ply laminates[*6*]. This analysis was extended to include combined bending and torsion in Ref. *7* and combined extension, bending and torsion loads in Ref. *8*.

It is found that this analytical method can also be applied to unsymmetrical laminate under uniform extension. This is of significant practical implications as damage modes often alter the initial symmetry existing in laminate designs. Moreover, unsymmetrical laminate designs are also used for elastic tailoring. Potential delamination sites in a $[-q/(90-q)_2/-q/q/(q-90)_2/q]_T$ class of laminates were predicted based on the interlaminar stresses and the total strain energy release rate. This class of laminates is designed to exhibit extension-twist coupling with no initial warping due to curing stresses.

A computational scheme was developed in order to predict the onset of delamination. The analysis involves two steps. In the first step, potential delamination sites or critical interfaces are determined. This is done by assuming delaminations at the free edges of one interface at a time and predicting the sign of the interlaminar peel stress in the neighborhood of the delamination-tip. The closed form expressions provided by the analysis makes it possible to perform this procedure at minimum computational effort. A positive peel stress represents a potential critical interface. In the second step a complete analysis of the laminate is performed with delamination at the free edges of the critical interfaces. The predicted delamination sites based on the interlaminar peel stress is consistent with the total strain energy release rate prediction.

The results of this research are presented in Ref. *9*. To the best of our knowledge this is the first closed form fracture analysis model for unsymmetrical laminates.

The potential benefits of applying extension-twist coupled laminates in rotorcraft composite structures provided the motivation for assessing the $[-q/(90-q)_2/-q/q/(q-90)_2/q]_T$ class of laminates and developing means for maximizing coupling under mechanical loads while ensuring hygrothermal stability.

Analysis of Laminates with Optimum Extension-Twist Coupling

The shear deformation model developed for unsymmetrical laminates was applied to the design and analysis of laminates with optimum extension-twist coupling. This is also a prerequisite to assessing the effect of damage in laminated composites designed for maximum coupling. A constrained optimization scheme was developed in order to determine the stacking sequence that maximizes the extension-twist coupling in a composite laminate while maintaining its hygrothermal stability [*10*]. The results were compared with the hygrothermally stable laminates obtained by stacking a set of rotated [0/90] plies such as the $[-q/(90-q)_2/-q/q/(q-90)_2/q]_T$ class of laminates . It was found that the laminate configurations resulting from the optimization scheme have improved coupling. Their coupling magnitude however, is very sensitive to changes in fiber angle. This restricts their implementation in practical designs.

Eight sets of laminates with varying extension-twist coupling were made in house with Hercules AS4/3502 Graphite/Epoxy and tested using a custom loading transducer. The laminates test results were compared with analytical predictions from the analytical model developed and from Classical Lamination Theory (CLT). It was found that shear deformation has a negligible influence on the extension twist coupling and predictions from both theory were in close agreement.

The result of this work indicate that the hygrothermally stable laminates obtained by stacking a rotated 0/90 group of plies provide optimum extension-twist coupling and robustness. Moreover, the extension-twist coupling in this class of laminates is accurately predicted by Classical Lamination Theory.

Effect of Free-edge Delamination on Extension-twist Coupling:

The optimum configurations achieved in Ref. *10* are the basis for assessing the influence of damage on elastically tailored laminates. Eight sets of laminates with embedded free-edge damage were fabricated in house with Hercules AS4/3502 Graphite/Epoxy and $[30/\text{-}60_2/30/\text{-}30/60_2/\text{-}30]_T$ layup. The damage was simulated by placing a thin Teflon FEP film along the length of the specimen at two locations. The first, placed at the mid-plane free edges (30/-30 interface), while the second, symmetrically placed at 60/60 and 60/-60 interfaces. The damage was symmetrically stacked in the second configuration, in order to avoid warping due to curing stresses.

The specimens were tested under uniaxial loading and the associated end-twist was recorded. The results showed a reduction of 18.5% from the undamaged state for mid-plane delamination and a reduction of 13.1 % for off mid-plane delamination [*11*].

Analysis and Failure Prediction in Composite Stiffeners:

An illustration of the ability of the developed analytical models to predict damage onset and growth at the component level as well, is provided in Refs. *12-15*. These include composite plates and stiffeners subjected to compressive loads. Of significance, is the result of Ref. *15* where the failure sites observed in tests of composite stiffeners are explained based on the interlaminar stress field associated with the postbuckled configuration. This correlation was shown in Ref. *9* for damage onset prediction in unsymmetrical laminates. A similarity between failure prediction based on interlaminar stresses and strain energy release rate was also established.

Lessons Learned and Future Investigation:

Among the findings of this research work, three lessons have significant implications. The first, is the similarity in analytical modeling between symmetrical laminates subjected to applied combined loads and unsymmetrical laminates subjected to separate loading. In the latter the combined loading effect is induced by the intrinsic coupling associated with the unsymmetry. The second, is the similarity in failure predictions between stress based models and strain energy release rate approaches. Finally, free-edge delamination can have a significant effect on the coupling stiffness of a laminate while its influence on the axial stiffness is negligible. The variation in the coupling stiffness depends on the delamination site and can be detected at a low level of loading. This finding points to a basic inquiry, namely, how a given damage mode affects the various anisotropic stiffness coefficients of laminated composites. Also, if the variation in a stiffness coefficient could be directly correlated to a given damage mode and site. These inquiries provide the motivation for the proposed structures and materials research task on damage characterization and analysis of unsymmetrical laminates.

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External Interactions

A number of briefings has been made to the Army Aerostructures Directorate at NASA Langley and Sikorsky Aircraft. The sublaminate analysis of laminates subjected to bending and combined loads was provided to Dr. Habib Rai of Bell Helicopter. The analysis of unsymmetrical laminates was given to Dr. Ronald Zabora of Boeing Commercial Airplane, Dr. Roderick Martin of NASA Langley and Dr. Steven Hooper at Wichita State University. The analysis and design methodology of laminates with optimum extension-twist coupling were provided to Dr. Ran Kim of the University of Dayton Research Institute.

IV. Flight Mechanics and Controls

Task 1. Modern and Active Control Research for Rotorcraft Applications

A.J. Calise, D.P. Schrage and J.V.R. Prasad

Problem Studied

This task is devoted to exploring robustness and controller order reduction issues related to the design of rotorcraft flight control systems, and active control of blade modal responses to disturbances and pilot inputs. The objectives are to develop a methodology for designing fixed order dynamic compensators in an optimal output feedback setting. The design approach should allow for a direct means of trading off performance and robustness measures. Applications to rotorcraft flight control, and active control of rotor dynamics and blade modal responses have been investigated. Robustness to both unstructured uncertainty and to structured parameter uncertainty have also been addressed. For simultaneous control of rigid body and aeroelastic modes, a two time scale design approach was developed based on Singular Perturbation Theory. Nonlinear transformation techniques are also being investigated which provide a means of developing invariant controllers that give a desired response in all flight modes.

Summary of Results

During this period we have continued our work to develop necessary and sufficient conditions for designing fixed order dynamic compensators that satisfy an H_∞ bound, and which in the limit as a parameter is reduced will permit the calculation of the optimal fixed order H_∞ controller. We are very close to completing the sufficiency part of the proof, and have gained considerable insight into the conditions that must be imposed before sufficiency can be demonstrated. Several fairly large order flight control examples are also being developed which will be used to illustrate the methodology and benefits of fixed order compensation. A paper is currently being prepared for submission to the Decision and Control Conference in which we hope to summarize the developments.

We have also initiated a new effort to improve the numerical method used to compute an optimal output feedback gain. This area remains a major stumbling block to the development of reliable software for optimizing the gains in a fixed compensator structure. Two approaches are currently under investigation. The first uses a novel homotopy method which starts with the solution for full state feedback, and progress to the output feedback solution by following the solution path for a set of algebraic equations as a scalar parameter is varied from zero to one. When the parameter is zero, solution of the algebraic equations is equivalent to the full state feedback solution. When the parameter is one, the solution solves the output feedback problem. The potential advantages to this approach are: (1) it eliminates the need for specifying an initially stabilizing output feedback gain (needed as a starting point for the current algorithm), and (2) if the solution path (which is followed by performing a quadrature) does not contain a singularity the optimal output feedback solution is obtained without the need for iteration. The second approach entails modifying the current iterative sequential algorithm so that it searches only over the set of internally stabilizing output feedback gains. A major deficiency in the existing approach is that it often takes a search direction which may lead to destabilizing gain for a very small step.

When this occurs, the algorithm fails to find a minimizing solution, even though we have developed a proof that for a sufficiently small step, the performance index can always be reduced. The difficulty is that it is possible that the improving step may become arbitrarily small, and the resulting improvement may not be computable within machine precision. It is hoped that by restricting the search to internally stabilizing gains, this difficulty will be avoided. This restriction entails enforcing a linear constraint on the controller gains in the search process. We have developed a proof of convergence for a sequential algorithm which shows that given an initially stabilizing gain which doesn't necessarily satisfy the constraint, the constraint will be satisfied after a finite number of steps and remain satisfied thereafter in each iteration of the search process.

During this period we have considered approximate full model inversion for nonlinear controller synthesis using the feedback linearization technique. The control terms that appear in the nonlinear equations were approximated in terms of a control sensitivity matrix in order to simplify the inversion process. Dynamic inversion essentially involves inversion of control sensitivities in order to calculate the required control movements. In the helicopter case, certain control sensitivities are very small, e.g., cyclic control sensitivities on body axis accelerations are generally very small. It is seen, using the full model inversion results, that the effect of small control sensitivities is to cause significant control chattering and as the bandwidth of the controller is increased, not only does the chattering increases in frequency but also the closed loop system eventually goes unstable. It is felt that an alternate way to use an approximate model that includes terms containing products of system states and controls. We are currently investigating the alternate approach. Also, during this period, we have conceptualized a general procedure for synthesizing robust nonlinear controllers for helicopters. The procedure involves the use of system identification techniques for obtaining an approximate nonlinear model of the helicopter in polynomial form of prespecified degree. Then approximate linearization techniques are used to transform the approximate nonlinear model into linear domain. The issue of describing maximum bounds on uncertainties, that are needed for robust controller design in the linear domain, can be addressed using fit errors between flight test data used in the identification step and response data computed using the approximate model. Finally, linear controller synthesis is performed on the transformed system in order to find the feedback laws necessary to obtain performance in the presence of uncertainty. A paper describing this approach has been accepted for presentation at the 1993 Annual Forum of the American Helicopter Society.